

Energy end-use and efficiency potentials among Swedish industrial small and medium-sized enterprises – A dataset analysis from the national energy audit program



Elias Andersson*, Magnus Karlsson, Patrik Thollander, Svetlana Paramonova

Department of Management and Engineering, Division of Energy Systems, Linköping University, SE-581 83 Linköping, Sweden

ARTICLE INFO

Keywords:

Energy end-use
Conservation supply curves
Energy efficiency
Industrial energy efficiency
Energy efficiency measures

ABSTRACT

Improving energy efficiency in industry is recognized as one of the most vital activities for the mitigation of climate change. Consequently, policy initiatives from governments addressing both energy-intensive and small and medium-sized industry have been enacted. In this paper, the energy end-use and the energy efficiency potential among industrial small and medium-sized companies participating in the Swedish Energy Audit Program are reviewed. The three manufacturing industries of wood and cork, food products and metal products (excluding machinery and equipment) are studied. A unique categorization of their production processes' energy end-use is presented, the results of which show that the amount of energy used in various categories of production processes differ between these industries. This applies to support processes as well, highlighting the problem of generalizing results without available bottom-up energy end-use data. In addition, a calculation of conservation supply curves for measures related to production processes is presented, showing that there still remains energy saving potential among companies participating in the Swedish Energy Audit Program. However, relevant data in the database used from the Swedish Energy Audit Program is lacking which limits the conclusions that can be drawn from the conservation supply curves. This study highlights the need to develop energy policy programs delivering high-quality data.

This paper contributes to a further understanding of the intricate matters of industrial energy end-use and energy efficiency measures.

1. Introduction

The mitigation of climate change remains a key challenge for national governments. One of the primary means for mitigating greenhouse gas emissions from industry is through policies improving energy efficiency [1]. The European Union's energy efficiency target of 20% by 2020, set by the European Commission [2], has been subject to a proposal for an update to a 30% target by 2030 [3]. The global energy efficiency potential for the industry has been estimated to be about 25%, although this only considers technological diffusion [4]. Studies have shown a higher potential if energy management is also included [5,6].

The major policy initiatives involving the industrial sector have been directed towards energy-intensive industries (see for example [7,8]), but national attempts primarily involving energy audit programs have also been designed to meet the needs of industrial small and medium-sized enterprises (SMEs) [9,10]. Still, about 90% of the energy

end-use (EEU) in Swedish industry emanates from energy-intensive industries [11]. About 70% stems from large industrial companies. Thus, the major scientific field of research has naturally paid most attention to large and energy-intensive companies.

Suggestions for policies to improve energy efficiency in energy-intensive industries were made by Napp et al. [12]. Thollander et al. [13] analyzed policies directed towards industrial SMEs in several countries, distinguishing between medium-sized and energy-intensive SMEs and small-sized and non-energy-intensive SMEs. For the former, it was concluded that Energy Conservation Law, Long-Term Agreements and Voluntary Agreements are strong EEU efficiency policies, followed by energy audit programs, preferably operated locally. For the latter, energy audit programs are to be preferred, followed by local energy networks and investment subsidies. In medium-sized and energy-intensive SMEs, the share of production processes in the total EEU is higher than in small-sized and non-energy-intensive SMEs, as shown by Thollander et al. [14].

* Corresponding author.

E-mail addresses: elias.andersson@liu.se (E. Andersson), magnus.karlsson@liu.se (M. Karlsson), patrik.thollander@liu.se (P. Thollander), svetlana.paramonova@liu.se (S. Paramonova).

<https://doi.org/10.1016/j.rser.2018.05.037>

Received 31 December 2016; Received in revised form 15 May 2018; Accepted 16 May 2018

Available online 25 May 2018

1364-0321/ © 2018 Elsevier Ltd. All rights reserved.

The Swedish Energy Audit Program (SEAP) was conducted during 2010–2014, subsidizing energy audits for industrial SMEs. The SEAP has previously been evaluated by Backlund and Thollander [15], based on the data from the first three years. Their results showed that the average energy efficiency potential per firm was between 860 and 1270 MW h/year, and that the highest energy efficiency potential was found in support processes, especially ventilation and space heating. Backlund and Thollander [15] further present an implementation rate of all suggested measures in the SEAP of around 53%, leading to an implemented energy efficiency improvement per firm of between 460 and 660 MW h/year. The total investment costs per firm varied between €74,100 and €113,000, or between €125 and €183 per MW h saved.

An ex-post evaluation based on data for the whole running time of SEAP was performed by Paramonova and Thollander [16], showing that the program resulted in net energy efficiency improvements equivalent to 340 GW h/year. This corresponds to 6% of the EEU of the analyzed companies (713 companies) with a 53% implementation rate. The largest energy saving potential was found in the support processes space heating (26%), ventilation (26%) and lighting (8%), and the average energy efficiency potential per firm was found to be 440 MW h/year [16]. Paramonova and Thollander [16] also calculated a total investment cost per firm of €214,060 or €520/MW h, and a cost-effectiveness of the SEAP was €700/measure or €7/MW h. These calculations were made considering net-present value and both free-rider and spillover effects.

In the SEAP database, the EEU of support processes was categorized according to a taxonomy which considers unit processes, founded by Söderström [17] and shown in a modified version in Table 1. However, the SEAP considered production processes to be one single category. The importance of developing a general taxonomy that can be used as a standard tool was highlighted by Thollander et al. [14], who revealed heterogeneity of data quality in different countries, leading to uncertainties concerning the actual EEU and energy efficiency potentials.

Conservation supply curves (CSCs) were developed in the early 1980's to evaluate and identify cost-effective energy efficiency measures (EEMs) [18]. CSCs identify energy saving potential, rank different EEMs against each other, and have been used in multiple industries (e.g. the ammonia industry [19], cement industry [20–25] and iron and steel industry [22,26]). CSCs have also been constructed to calculate the cost of conserving specific energy fuels, like the cost of conserved steam [27] or electricity [20]. CSCs are also used to evaluate CO₂ abatement [28].

While CSCs can identify the most cost-effective EEMs in industrial sectors, there is still a need to overcome barriers to the implementation of EEMs. A definition of barriers was given by Sorrell et al. [29], and a later contribution made by Cagno et al. [30] offered further developments. This was investigated, for example, for the non-energy-intensive manufacturing SMEs by Trianni and Cagno [31], and for the foundry industry by Rohdin et al. [32]. Also, a review of barriers to energy efficiency in industrial bottom-up energy-demand models was conducted by Fleiter et al. [33]. As well as calculating CSCs for the cement industry, Tesema and Worrell [21] also highlighted the importance of overcoming barriers to the implementation of EEMs.

The aim of this paper is to review the EEU along with energy efficiency potential among industrial SMEs in three different industries by using the SEAP database. This was achieved in two steps. Firstly, the EEU of production processes was categorized according to the unit process concept. Secondly, CSCs for real suggested measures, derived from the SEAP database, for production processes were constructed. Separate CSCs were constructed for conserved electricity and conserved fuel, as well as for implemented measures and non-implemented measures.

This study allows for a unique bottom-up analysis of real EEMs for a sample of industrial SMEs, and enables a comparison between implemented and non-implemented measures, serving as an important contribution to understanding the energy efficiency potential of

Table 1

Unit processes considered in the categorization of EEU (based on Söderström [17])^a.

Production processes	Support processes
Disintegrating	Space heating
Mixing	Space cooling
Disjointing	Lighting
Joining	Ventilation
Coating	Administration
Molding	Tap water heating
Heating	Compressed air
Melting	Transports
Drying	Other
Cooling/freezing	
Packing	
Other/impossible to categorize	

^a The production processes in this table are categorized according to the unit process taxonomy presented by Söderström (1996), while the support processes follow the categorization of support processes in the SEAP, which differed slightly from the concept of unit processes.

industry in general and industrial SMEs in particular.

2. Methodology

The paper conducts an analysis of the following three manufacturing industries:

- Manufacture of wood and of products of wood and cork (C16¹)
- Manufacture of food products (C10¹)
- Manufacture of fabricated metal products, except machinery and equipment (C25¹)

In this paper, these industries are designated: *wood industry*, *food industry* and *metal industry*. The study is based on both the energy audit reports, which were performed between 2010 and 2014 within the SEAP, and the database derived from this program. The number of SMEs joining the SEAP were 30 for the wood industry, 27 for the food industry and 79 for the metal industry.

Firstly, using the SEAP database, a categorization of EEU was conducted for these industries. As the EEU data for support processes were already categorized in the SEAP database according to the categories in the right-hand column of Table 1, it is presented as is. However, since the production processes are categorized in the SEAP database as one category (called production processes), the EEU in production processes had to be allocated to the unit processes, as shown in the left-hand column in Table 1. This was done by studying the energy audit report for each included industrial SME, where the EEU of production processes was allocated to the relevant unit processes. A considerable amount of the EEU could not be categorized due to production processes being considered as a whole in many of the energy audit reports, or categorized in a way that can be understood only by internal staff of the company (e.g. Production line 1, codes of machines etc.).

In this study, real EEMs for production processes, as suggested by energy auditors in the SEAP, were used for calculating the CSCs. Notably, since energy auditors in the SEAP seem to focus mainly on support processes, such as lighting, the identified measures for production processes might only cover a proportion of the possibly existing EEMs in production processes, which may imply a limitation to the overall energy saving potential in the studied industries. To construct a CSC diagram, the energy savings and the specific cost of conserved energy (CCE) were used. In the SEAP database, no distinction is made as to what type of energy carrier is saved by an EEM, only the amount of

¹ Statistical classification of economic activities in the European Community (NACE), following the second revision NACE Rev. 2.

energy saved by each measure is presented. Therefore, in order to enable the calculation of specific CCE for electricity and fuels, respectively, the type of energy carrier saved was controlled in the energy audit reports for each EEM. For measures that conserved both electricity and fuel, all of the saved energy was assumed to be conserved fuel, since it was not always possible to derive the share of each energy carrier.

In this paper, the terms “efficiency” and “savings” are used interchangeably. The term “fuel” is used for all energy carriers apart from electricity.

The CCE for a measure is calculated according to Eq. (1).

$$CCE = \frac{\text{Annualized capital cost} + \text{Annual change in operation and management costs}}{\text{Annual energy savings}} \quad (1)$$

Where the annualized capital cost is calculated according to Eq. (2).

$$\text{Annualized capital cost} = \text{Investment cost of measure} \cdot \left(\frac{d}{1 - (1+d)^{-n}} \right) \quad (2)$$

Where d is the discount rate and n is the lifetime of the EEM. Since no information is given regarding either discount rate or lifetime in the SEAP database, the discount rate is assumed to be 7% for all measures, and the lifetime is assumed to be 12 years for investment in new technology and five years for management measures, similar to Backlund and Thollander [15]. In this paper, management measures are assumed to be reduced stand-by losses, to align with the categories in the available dataset. Furthermore, no information on changes in operation and management costs were available; therefore, these are assumed to be zero for all measures. Fleiter et al. [34] showed that CSCs are sensitive to variables such as discount rate, energy prices, decisions concerning the methodology (for example, whether energy taxes or non-monetary costs are considered), and deficiencies or shortcomings in the methodology. The outcome of each CSC is affected by these simplifications and they must be considered when interpreting results.

The CCE is calculated for both conserved electricity and conserved fuel. In the SEAP database, all EEMs are marked whether they are planned to be implemented or not within the scope of the program, according to the reporting from the companies. In this paper, separate CCEs are calculated for non-implemented and implemented EEMs to enable a unique analysis and comparison of measures. A couple of the EEMs in the database did not imply any saving of energy, and were therefore omitted. It should be noted that, since unique EEMs are studied, as identified by energy auditors at each company, the conservation potential does not cover the entirety of Swedish industry, but only the sample of companies studied. Furthermore, since the conservation options are based on the conducted audits, it is likely that additional, unidentified measures exist.

While the SEAP database allocated all EEU of production processes into one single category, each suggested EEM that concerned production processes was labeled by the authors as one of six categories, as shown in Table 2. The categorization of EEMs in the SEAP database is different from the categorization of EEU. This information is valuable for distinguishing which specific types of measures are common and

cost-effective among industrial SMEs in the studied industries.

CSCs may also be constructed for EEMs for support processes. However, this was not included in this study, due to lack of space for such a presentation and discussion. In Fig. 1, the approach adopted in the study is visualized.

3. Results and analysis

3.1. Energy end-use of studied industries

The EEU for production processes in the three industries are summarized in Fig. 2, divided into the unit process concept.

The share of the production processes is different depending on the industry; however, heat-related processes such as heating, drying and melting constitute a considerable share of the EEU in all three industries. In the wood industry, the energy use for drying is very high, not just in terms of share (almost 70%), but also in absolute terms (GW h/year). Disregarding EEU related to “other” or “impossible to categorize”, drying is also the largest EEU production process in the food industry, accounting for 18% of the total EEU for production processes, while molding takes the largest share for the metal industry, accounting for 23%.

The total EEU for production processes is higher in the wood industry than both of the other two industries, even though the number of companies analyzed in the wood industry is less than half of those in the metal industry. Consequently, the wood industry has the highest average energy use per company and year of 12,200 MWh, followed by the food industry with an average of 4900 MWh, and the metal industry with 2800 MWh.

The EEU for support processes in the three industries is summarized in Fig. 3. As these are pre-defined categories used in the SEAP, the EEU for support processes is presented accordingly.

As may be noticed in Fig. 3, space heating is the largest EEU of the support processes in all studied industries. It is also shown that, compared to the other industries, the share of ventilation and lighting is largest for the metal industry, the share of transport is largest for the wood industry and the share of space cooling and tap water heating is largest for the food industry. The average energy use for support processes per year and company is 3200 MWh for the wood industry, 2500 MWh for the food industry and 2000 MWh for the metal industry.

The EEU for processes, divided into production processes and support processes in the three industries, is summarized in Fig. 4. The majority of the EEU is found in production processes, but the share used by support processes for the metal industry is almost half the total EEU.

3.2. Energy savings and conservation supply curves by ID of the studied industries

The total savings for electricity and fuel, respectively, as given by the EEMs related to production processes, are summarized in Table 3. The highest total fuel-saving potential is found in the wood industry, followed by the food industry and, lastly, the metal industry. The highest total electricity efficiency potential is found in the metal industry, followed by the wood industry and, lastly, the food industry.

The EEMs for production processes in the SEAP database were categorized according to the ID-categorization shown in Table 2. Each EEM is presented separately in Appendix A. In Table 4, the number of implemented and non-implemented measures for each ID is shown. The implementation rate of the EEMs considered in this study, i.e. measures for production processes in the three studied industries, is 67% (72% for the wood industry, 59% for the food industry, and 66% for the metal industry). Regarding production processes for all industries in the SEAP, the implementation rate is 58% [15]. Considering all EEU processes for the entire SEAP, an average of about 4.5 implemented measures (implementation rate of 53%), and 440 MW h/year were saved per audited company [16]. For comparison, the German energy audit

Table 2
Categorization of the EEMs for production processes (ID-categorization).

Category ID	Type of measure
1	Power regulation of the processes
2	Reduce stand-by losses
3	Increase efficiency of the process
4	Conversion to another energy carrier
5	Switch to energy-efficient motors
20	Other

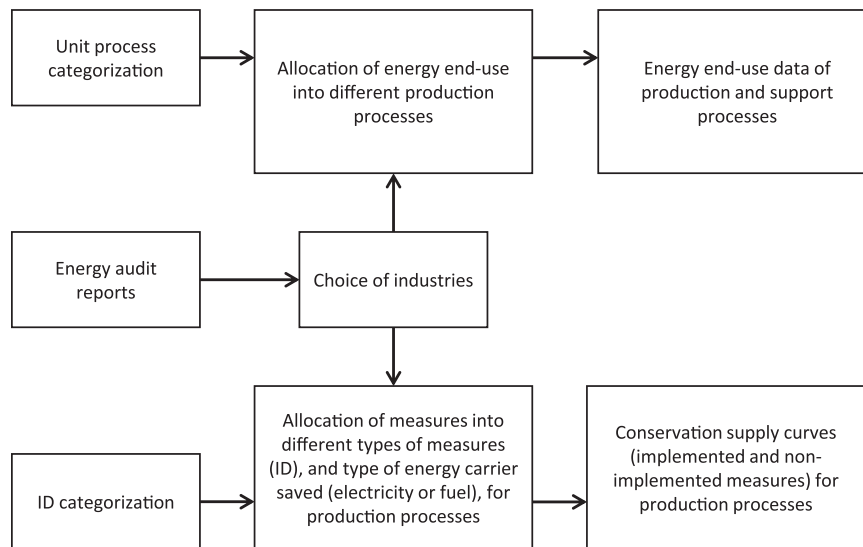


Fig. 1. Approach adopted for the study. The energy audit reports are the documents that enable the allocation of EEU into production processes.

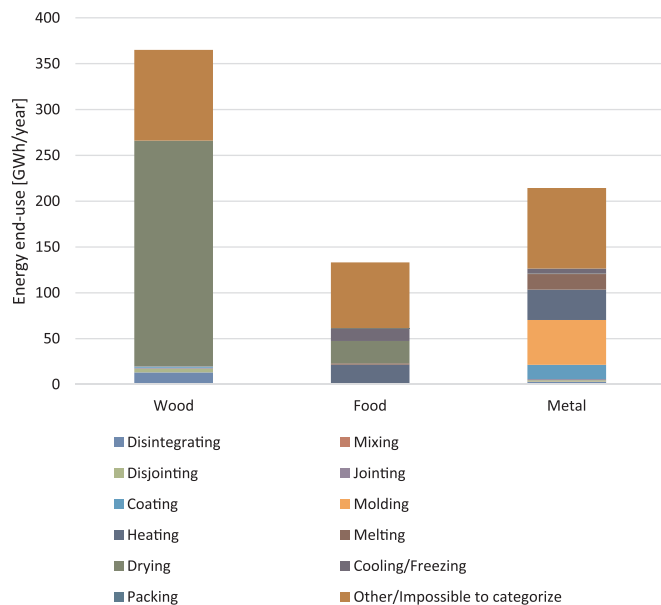


Fig. 2. Annual EEU for production processes in the three studied industries.

program revealed 1.7–2.9 implemented measures per company (implementation rate of 43%, or 72% if also considering planned measures) and energy savings of 70 MWh/year and audited company [9]. One reason for the higher implementation rate of EEMs in this study, in particular in the wood and metal industry, might be that measures for production processes in these two industries are relatively easy to implement since production processes in these industries are generally less complex than in, for example, the food industry. Some EEMs in the food industry require substantial investigations to meet hygiene requirements and furthermore, concern a number of connected support processes within the actual production processes, which is less applicable to EEMs in the wood and metal industries.

Electricity CSCs, including both implemented and non-implemented EEMs, are shown in Fig. 5, for the three studied industries. One measure categorized as ID 3 in the wood industry, which concerned the irrigation of timber, was omitted due to its high CCE (13,489 SEK/MWh), and was considered an outlier.

The largest electricity savings in the wood and food industries are given by measures which increase the efficiency of the process (ID 3),

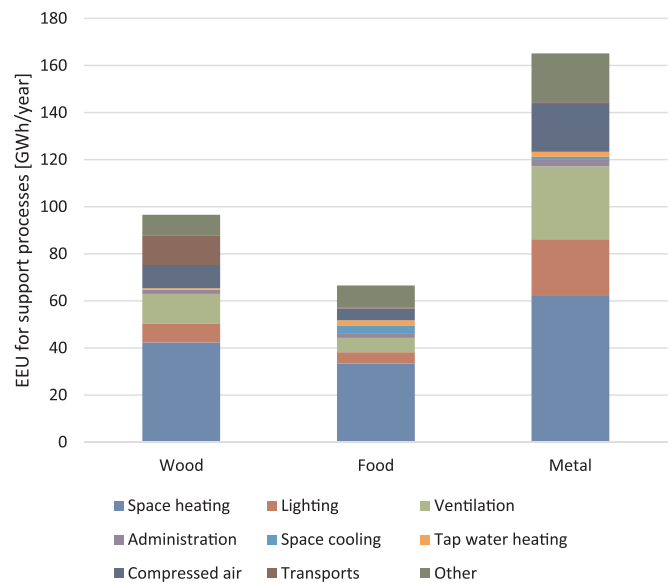


Fig. 3. Annual EEU for support processes for the three studied industries.

while for the metal industry the largest savings are gained through reduced stand-by losses (ID 2). Due to the variety of measures, and the fact that the categories are quite broad, the CCE of each category varies considerably from industry to industry. Power regulation of the processes (ID 1) has the lowest CCE for the wood industry, while ID 2 has the lowest CCE for the metal industry, and ID 20 for the food industry. It is also shown that the wood industry has zero electricity savings from conversion to other energy carriers (ID 4) and a switch to energy efficient motors (ID 5). For the food industry, there are zero electricity savings from power regulation of the processes (ID 1), or from reduced stand-by losses (ID 2). For the metal industry, the electricity saving potentials from IDs 1, 4 and 5 are rather low.

Fig. 6 shows the fuel CSCs, including both implemented and non-implemented EEMs, and it is clearly shown that the largest amount of fuel savings stems from increased efficiency of the process (ID 3) in the wood industry, more than 24,000 MWh/year. These EEMs relate to a large degree to the wood-drying process, where a majority of the heat is used, as well as a large share of the total energy used in the wood industry (Fig. 2). EEMs categorized as ID 3 account for the largest fuel savings in the other industries as well. Notably, it is the only type of

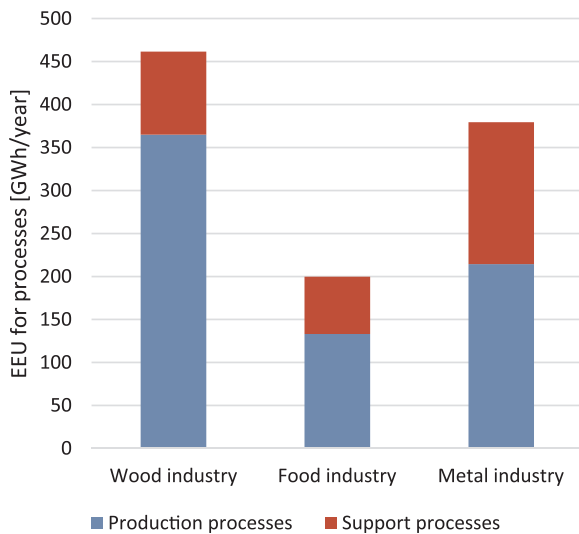


Fig. 4. EEU for production and support processes for the wood, food and metal industries.

measure regarding fuel that is represented in the metal industry (in total two measures), showing that mostly electricity is used in the production processes of the metal industry. The type of measure with the lowest fuel CCE in the wood industry is power regulation of the processes (ID 1), and in the food industry measures categorized as other (ID 20). Three of the five types of measure across the studied industries with lowest CCE account for quite small total fuel savings.

3.3. Electricity conservation supply curves for each energy efficiency measure

Figs. 7–9 show the implemented and non-implemented measures in which electricity is saved separated for each of the studied industries. It can be noticed in these figures that the CCE of the implemented EEMs in a certain category is not always lower than the CCE of the non-implemented EEMs in the same category.

From Fig. 7 it is possible to discern that a majority of the cost-effective measures have been implemented by the wood industry. Still, seemingly cost-effective EEMs of at least 700 MWh in total remains unimplemented by the companies. The single largest non-implemented measure (EEM no. 25) corresponds to savings of 474 MWh, and is related to “intermittent operation of circulation fans in driers” but, according to the company’s reporting, it was not deemed possible to implement this in time before the completion of the SEAP. It was also one of many EEMs in the company, and only a share of the measures could be implemented.

The total electricity saving in the sample of industrial companies in the food industry is not as large as the total fuel saving potential. In Fig. 8, it is evident that among the studied industrial SMEs in the food industry there is as much unutilized electricity saving potential in the non-implemented EEMs as in the implemented measures, roughly 500 MWh. In other words, the electricity savings could potentially be

doubled. The two non-implemented EEMs with the lowest cost of conserved electricity (nos. 64 and 65) both relate to increasing the efficiency of the process (ID 3), and account for the largest share of the unutilized potential. The larger of these two was not implemented because it was part of another production process (increasing the efficiency of “Packing”) rather than the process in which the company was currently focusing its investments and energy efficiency improvements.

The metal industry has the largest number of suggested EEMs where electricity can be saved. In fact, only two of the measures suggested in the database correspond to savings of fuel. It is interesting to note from Fig. 9 that there is quite a large amount of energy saving potential with no investment costs (in total 696 MWh), and thus no CCE, that have not been implemented by the industrial SMEs in the studied sample. The reason for this might vary, but some of the EEMs given by energy audits have yet to estimate an investment cost, which in turn has resulted in a zero figure in the reporting supplied by the companies. The second largest, non-implemented measure stands for savings of 650 MWh (no. 131) and concerns stand-by losses for machines. The reason given by the company for not implementing this measure is that it is not practical, but no further explanation is given. For the other measures with no investment cost, no clear reasons are given either. Nevertheless, the results suggest in general that SMEs in the metal industry should consider the possibility of reducing stand-by losses, as potentially a large amount of energy might be saved through this management measure.

The largest EEM found in the database for the studied sample in the metal industry corresponds to electricity savings of 1000 MWh, at a CCE of 630 SEK/MWh (no. 149). This measure implied replacing the holding furnace with a modern furnace, and required a large investment of around 5 million SEK. The company planned to carry out the replacement and be finished a few years after the conducting of the energy audit. While the measure is not marked as “performed” in the SEAP database, by now it has most likely been implemented by the company.

In total, potentially cost-effective, non-implemented measures account for roughly 1500 MWh of electricity among the studied industrial SMEs in the metal industry. The third largest non-implemented, seemingly cost-effective measure (no. 142) concerned decreasing the temperature in the pre-treatment bath (in a metal surface treatment company), but was deemed not technically possible due to the need to adapt to the different characteristics of treated goods.

3.4. Fuel conservation supply curves for each energy efficiency measure

Figs. 10 and 11 show the implemented and non-implemented measures in which specific fuel is saved separated for the wood and food industries. No fuel CSC diagram is presented for the metal industry, because only two measures related to savings of fuel.

All of the suggested EEMs for the wood industry that concern conservation of fuel have a CCE of less than 350 SEK/MWh. Despite this, even though a majority of the measures have already been realized by this sample of companies, there is still about 11,000 MWh of identified, unutilized potential. The measure with the largest savings potential (no. 56) (5500 MWh) also requires a large investment (15 million SEK) to purchase a new boiler. According to the company’s reporting, this measure will be implemented in the long term, after the finalization of

Table 3

Summary of the energy savings for production processes, divided by implemented and non-implemented measures, as reported by the companies participating in the SEAP.

	Savings given by implemented measures [MW h]		Savings given by non-implemented measures [MW h]		Total savings [MW h]	
	Electricity	Fuel	Electricity	Fuel	Electricity	Fuel
Wood industry	3418	17,046	703	9268	4121	26,314
Food industry	535	2473	534	1436	1069	3909
Metal industry	2296	1500	2876	0	5172	1500

Table 4
Number of measures for production processes in the three studied industries for each ID.

	Wood industry		Food industry		Metal industry	
	Implemented	Not implemented	Implemented	Not implemented	Implemented	Not implemented
ID 1 - Power regulation of the processes	10	4	0	0	0	1
ID 2 - Reduce stand-by losses	7	2	2	1	26	13
ID 3 - Increase efficiency of the process	20	6	10	6	15	7
ID 4 - Conversion to another energy carrier	0	0	2	4	1	1
ID 5 - Switch to energy-efficient motors	0	2	0	1	1	0
ID 20 - Other	4	2	3	0	3	2
Total	41	16	17	12	46	24

the SEAP.

For the implemented measures, the four with the largest energy savings all concern increased efficiency (ID 3) of the drying process (generally the largest energy use process in sawmills). All of the implemented measures for the drying process in the industrial SMEs studied corresponded to a total of 14,431 MWh, or 95% of all the energy from the implemented measures for conservation of fuel. Due to this process corresponding to such a large share of the EEU (Fig. 2), it is likely to attract attention from energy auditors in getting knowledge about this specific process; consequently, many of the proposed measures for production processes will focus on the drying of wood. Another factor that might contribute to a larger share of suggested EEMs for the drying process is time constraints, making energy auditors focus on EEU processes that are assumed to have the largest energy saving potential, leaving other, less energy using production processes without suggested measures. Hence, for the wood industry and the other studied industries, there might still be energy efficiency potentials that are unidentified and thus not present in the results of this study.

Only a small share of seemingly cost-effective EEMs for the conservation of fuels was not implemented in the food industry, as seen in Fig. 11. Compared with the implemented measures, only two measures with lower CCE remain unimplemented. Regarding the one with lowest CCE, which recommended cold disinfection for cleaning of processes (no. 80), the company deemed the measure to need long-term testing of sanitary safety before implementation. For the EEM with second lowest CCE, which suggested the pre-heating of dishwater using district heating (no. 81), the technology was perceived as inappropriate at the specific site. From Fig. 11, it seems that the companies from the food industry that participated in the SEAP had implemented a majority of the cost-effective EEMs regarding conservation of fuels.

4. Concluding discussion

This paper gives a unique presentation of energy end-use (EEU) data categorization from manufacturing companies, based on the taxonomy developed by Söderström [17]. Data from industrial companies participating in the Swedish Energy Audit Program (SEAP) was used, representing the three manufacturing industries of wood, food and metal. Conservation supply curves (CSCs) were also calculated for these industries, for production processes only, based on different types of energy efficiency measures (EEMs) (IDs). The results show that the amount and share of EEU of the various production processes (molding, cooling etc.) differ widely between the industries, and that the same holds for support processes. The heterogeneous EEU of the studied industries is also demonstrated by the fact that the wood industry, despite accounting for a smaller number of companies than the metal industry, still had a larger share of EEU in production processes than the metal industry.

Even though production processes are the major energy-using processes in the studied industries, the EEU of support processes for some individual companies (34 out 139) accounted for more than 80% of their total energy use. This clearly illustrates the problem with generalizing results related to EEU and energy efficiency potentials too widely in the industrial sectors, without available bottom-up EEU data. It is also an indication of a heterogeneous manufacturing industry, especially when it comes to industrial SMEs.

Also, when energy data and energy audits were studied, deviations were found in how categorization of EEU data was made. This highlights the need for a harmonized categorization of EEU data and not the least for quality assurance of both EEU data and energy audits, as previously outlined by Thollander et al. [14]. A standard protocol for

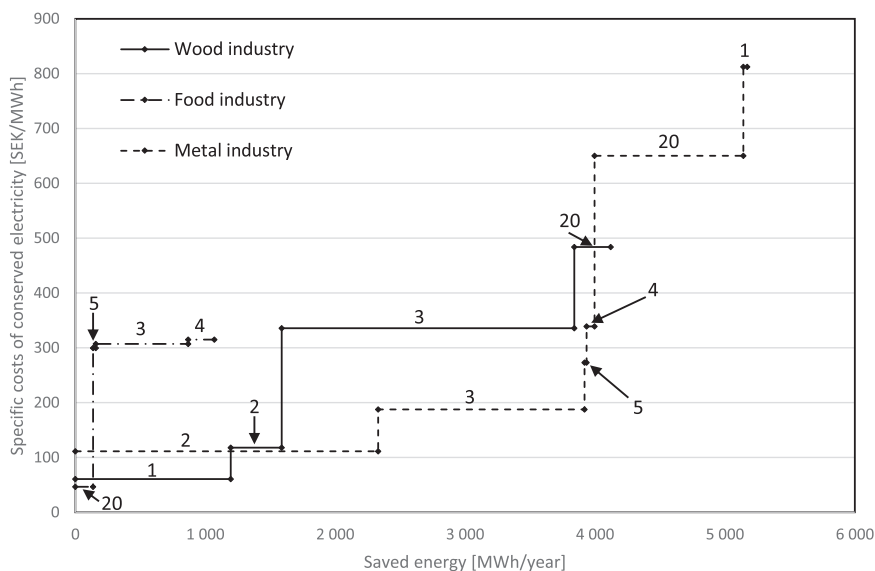


Fig. 5. Average electricity CSCs for all studied industries, categorized according to ID of EEM. Implemented and non-implemented measures are combined. The CCE is the average value of CCE for all EEMs in each ID. Standard deviations: wood industry (ID 1 = 109, ID 2 = 110, ID 3 = 418, ID 20 = 175), food industry (ID 3 = 377, ID 4 = 0, ID 5 = 0, ID 20 = 0), metal industry (ID 1 = 0, ID 2 = 174, ID 3 = 401, ID 4 = 24, ID 5 = 0, ID 20 = 672).

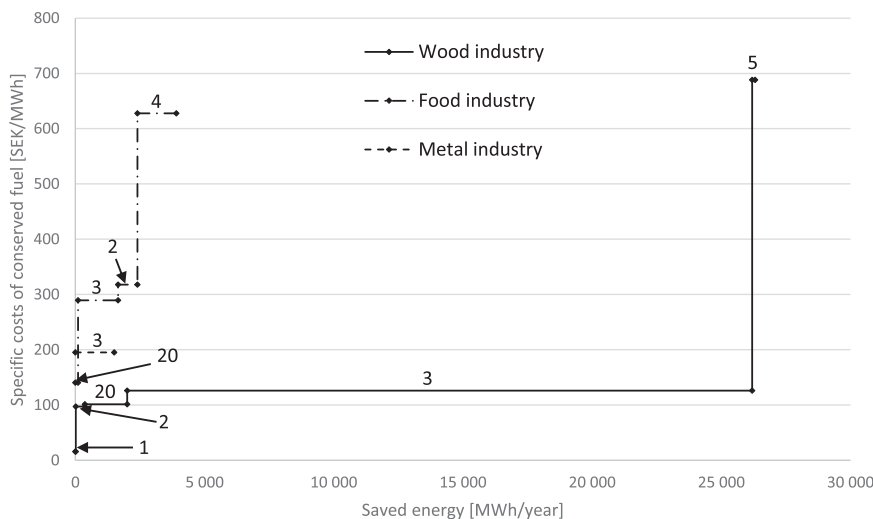


Fig. 6. Average fuel CSCs for all studied industries, categorized according to ID of EEM. Implemented and non-implemented measures are combined. The CCE is the average value of CCE for all EEMs in each ID. Standard deviations: wood industry (ID 1 = 0, ID 2 = 5, ID 3 = 113, ID 5 = 511, ID 20 = 25), food industry (ID 2 = 371, ID 3 = 211, ID 4 = 630, ID 20 = 40), metal industry (ID 3 = 6).

industrial companies when reporting EEU and EEMs, together with educational initiatives would be a big step towards generating high-quality data from energy policy programs in the future. This could possibly also decrease the amount of EEU categorized as “other”, which accounted for quite a large share in the studied industries. Moreover, a high quality of energy data is one necessary factor (of several) for achieving more reliable CSCs.

The energy audits in the SEAP mainly focused on support processes rather than production processes, as shown in Backlund and Thollander [15], in terms of the number of suggested measures. In this paper, only measures for production processes are considered in the calculation of CSCs, which is not only a limitation to the overall estimation of energy saving potential, but might also imply biased results. Nevertheless, the results show that production processes still have energy saving potential which, when compared to the total EEU for a single company, cannot be seen as infinitesimal. The calculated CSCs show that the categories of EEM having the lowest cost of conserved energy (CCE) in the studied industries differ, further emphasizing the need for bottom-up, industry-specific data. It can also be noted that the CCE of the implemented EEMs in a certain category is not always lower than the CCE of the non-implemented EEMs in the same category, indicating that cost

is not the only factor that is considered when making decisions about EEM implementation.

Regarding the implementation of EEMs, it should be noted that the time frame under study is around two years. This means that non-implemented measures could in theory be conducted after the two-year time frame, given that information on EEMs is still available. The companies had to state the reason for not implementing an EEM in their reporting to the SEAP, but the reasons given were not always fully clear. However, sometimes it was apparent that they related to barriers found in the literature, such as heterogeneity, e.g. that it is not technically possible to implement a measure, or lack of capital, enabling only a limited number of measures to be implemented.

The calculated CCE in this study assumed a lifetime of 12 years for technical measures and five years for management measures, similar to Backlund and Thollander [15]. In addition, the discount rate was assumed to be 7%. These assumptions, as well as not considering changes in operations and management costs of measures, are important limitations, due to which the calculated CCEs will not fully reflect the real cost. The amount of energy saved from each measure, as presented in this paper, is derived from the studied dataset and is not affected by these assumptions, but the specific CCE is affected. For example, a

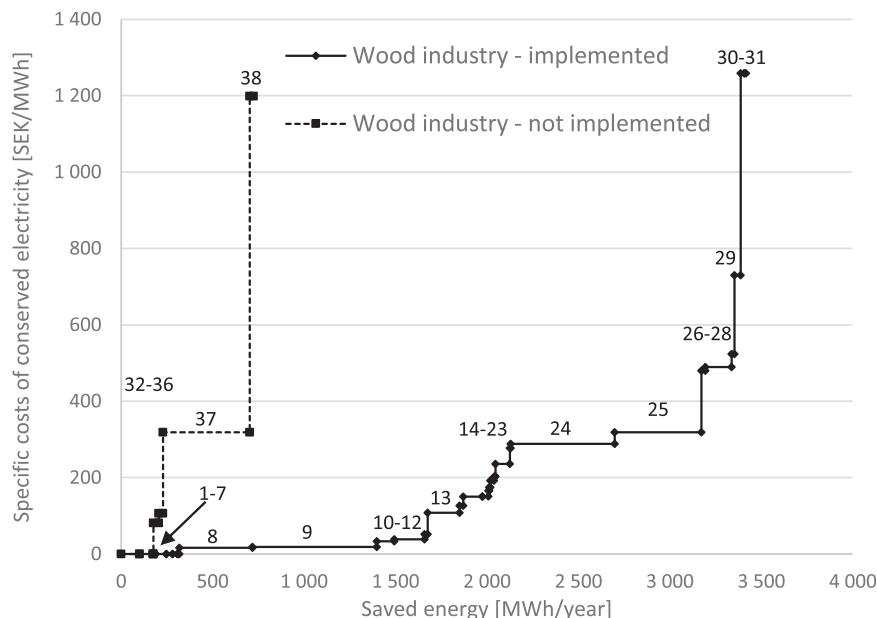


Fig. 7. Electricity CSCs for the wood industry – implemented EEMs and non-implemented EEMs separately. (Each EEM is numbered and found in Appendix A.).

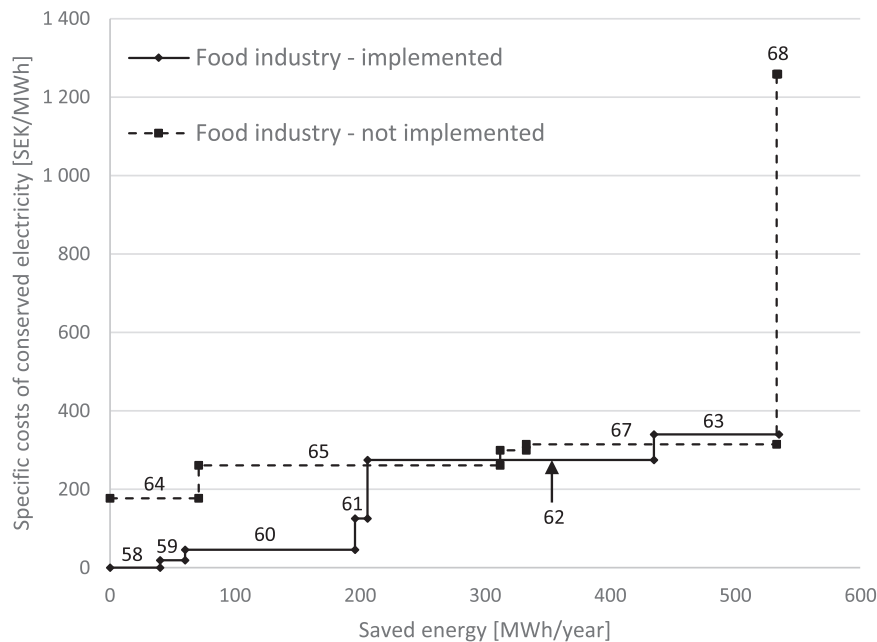


Fig. 8. Electricity CSCs for the food industry – implemented EEMs and non-implemented EEMs separately. (Each EEM is numbered and found in [Appendix A.](#)).

higher discount rate implies the same amount of energy saved, but the specific cost of conservation increases [34]. These limitations face the risk of creating an inaccurate estimation of the cost-effectiveness of the remaining energy saving potential of the industries studied in this paper.

In this paper, other benefits achieved from implementing energy efficiency measures were not considered, such as learning effects [34] but from a long-term perspective, including these may imply a lower specific cost of conservation. Lung et al. [35] included production benefits and ancillary savings in CSCs, using the approach of Worrell et al. [36], and achieved more cost-effective EEMs in comparison to when such benefits were not included. However, the additional benefits (e.g. non-energy benefits) of EEMs are yet to be monetized, as noted by Nehler and Rasmussen [37], but could be subject for further research, both for industrial SMEs and for energy-intensive industries.

Furthermore, the conservation potential is affected by e.g. quality of data (which implies either an increase or decrease in potential savings) and interactions of conservations (which imply a decrease of potential savings) [34]. Regarding the former, some corrections were made to the dataset used in this paper, such as inconsistencies in categorizing the type of EEM, but other errors might remain. In some cases, it was apparent that more than one measure was given for the same process; in such cases, the additional measures were omitted from the dataset.

A relevant issue is the risk of not applying a systems perspective, as the calculation of CSCs is based on separate EEMs for specific EEU processes. This does not consider, for example, how the measures affect the larger system of processes, thus being too focused on technological change, missing other opportunities that arise in continuous work with energy efficiency within an industrial company. Research by Paramonova et al. [6] and Svensson and Paramonova [38] of Swedish

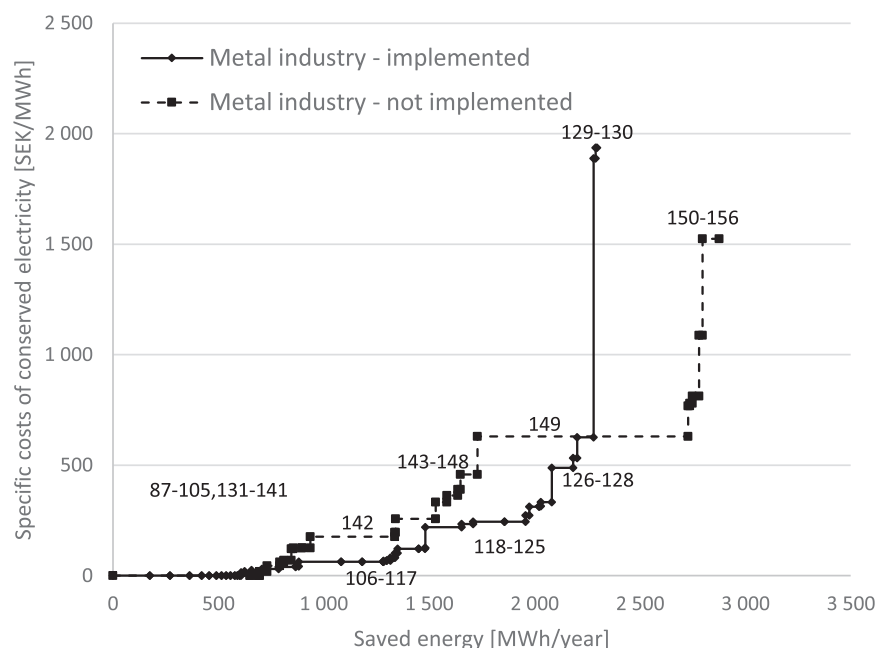


Fig. 9. Electricity CSCs for the metal industry – implemented EEMs and non-implemented EEMs separately.

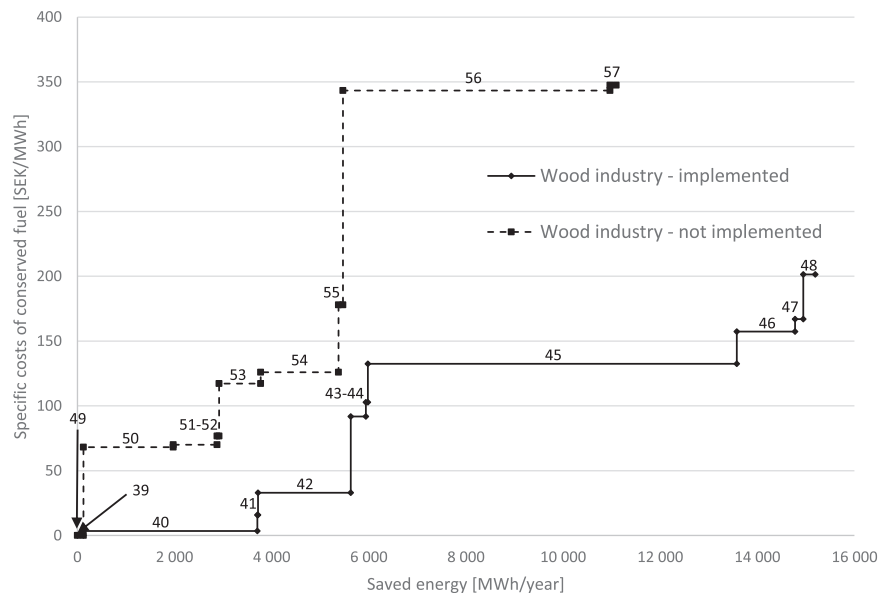


Fig. 10. Fuel CSCs for the wood industry – implemented EEMs and non-implemented EEMs separately.

energy-intensive industries and implemented EEMs reveals the risk of focusing on stand-alone technologies without considering energy management procedures and the complexity of processes mixed with each other. The inclusion of energy management practices extends the energy efficiency potential of manufacturing industry [5,6], and energy management is attracting increased interest among industrial companies [39].

The available dataset used in this study may not be seen as fully representative of the entirety of Swedish industry, as data from only three industries is displayed. One major improvement could be to validate findings, like the ones presented in this paper, with data for the whole of Swedish industry, since only a subset of industrial SMEs for the studied industries are considered in this paper. This would help in validating whether the energy savings are representative of the entire industry under study. However, the data from these three industries could not be validated using such national EEU statistical data, as it does not exist. What this implies is that governments are facing a

scarcity of available information about where energy is used, e.g. EEU processes, and how large the potential for improvement is in various areas. Improving research on EEU and energy efficiency, as well as supporting governments in their transition towards a more energy efficient economy, would naturally include creating larger quality-controlled datasets, aiming to close this information gap.

This paper has made an attempt to take a small step towards furthering our understanding of the intricate issues involved in industrial EEU and EEMs, and their interlinkage. The discussed shortcomings of CSCs should be accounted for as well as the hidden energy efficiency potentials that are found when extending system boundaries to include, among other things, non-energy benefits. In addition, more research is needed on where energy is used and its potential. This would provide a more prudent and sensible view on CSCs, as well as supporting decision-makers, from both industry and governments, on how to improve industrial energy systems in terms of energy efficiency.

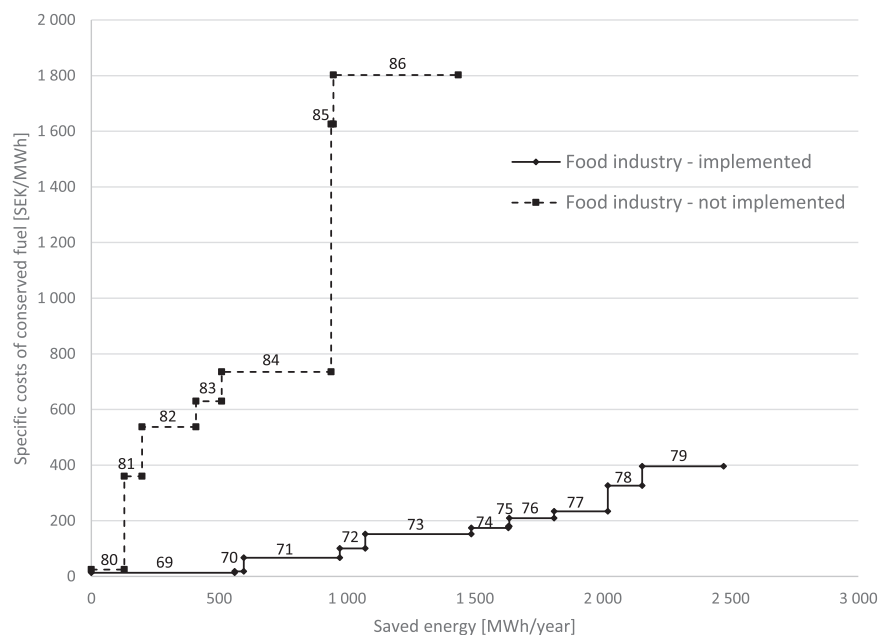


Fig. 11. Fuel CSCs for the food industry – implemented EEMs and non-implemented EEMs separately.

Acknowledgments

The authors of this paper wish to thank Gianluca Iori for valuable help in collecting and analyzing data, and for writing the initial draft of the paper under our supervision. We would also like to thank the

anonymous reviewers for valuable comments, which have considerably improved the quality of this paper. This work was supported by the Swedish Environmental Protection Agency (Research project Carbonstruct, project no. 802-0082-17) and the Swedish Energy Agency (Research project no. 40537-1).

Appendix A

See Appendix [Table A1](#)

Table A1

All energy efficiency measures for production processes as suggested in the Swedish energy audit program for the three studied industries. ID = the type of measure, CCE = cost of conserved energy.

No.	Measure	ID	Energy saved [MW h/year]	Energy carrier	CCE [SEK/ MWh]	Implement-ed [Yes/No]	Industry
1	Reduce power output during non-production hours	1	97	Electricity	0	Yes	Wood
2	Eliminate stand-by losses	2	92	Electricity	0	Yes	Wood
3	New saw routines	3	58	Electricity	0	Yes	Wood
4	Shut down chipper and conveyor belts in the regrading	1	35	Electricity	0	Yes	Wood
5	New saw routines	3	25	Electricity	0	Yes	Wood
6	Shut down the refrigerator dryer	1	7	Electricity	0	Yes	Wood
7	Relocate and shutdown unnecessary refrigerator and freezer installations	2	5	Electricity	0	Yes	Wood
8	Demand controlled dry air flow	1	400	Electricity	16	Yes	Wood
9	Control fan speed in wood drying kilns	3	680	Electricity	19	Yes	Wood
10	Optimization of circulation flows in OTC drying kiln	3	96	Electricity	33	Yes	Wood
11	Optimization of circulation flows in chamber dryer	1	165	Electricity	38	Yes	Wood
12	Relocate control of fan to the saw's cab	1	17	Electricity	52	Yes	Wood
13	Automatic dampers on the wood chip extractor and install frequency converters on three fan motors	1	175	Electricity	108	Yes	Wood
14	Install automatic damper and frequency converters on wood chip extractor	1	20	Electricity	126	Yes	Wood
15	Interlock conveyor belts over stop signals	1	105	Electricity	150	Yes	Wood
16	Shut down the saw's cutting function, conveyor belts and other motors	2	32	Electricity	151	Yes	Wood
17	Turn off the saw chip blower during non-working hours	3	4	Electricity	166	Yes	Wood
18	Turn off the hydraulic power unit in regrading	2	7	Electricity	174	Yes	Wood
19	Install engine heat controller at saw and log sorter	3	19	Electricity	192	Yes	Wood
20	Demand control system at bark conveyor belts	3	5	Electricity	201	Yes	Wood
21	Reduce idling of internal "trash" transport	2	3	Electricity	203	Yes	Wood
22	Overhaul the heat capacity of the VSAB drying kiln	20	80	Electricity	236	Yes	Wood
23	Turn off conveyor belts during lunch	3	4	Electricity	277	Yes	Wood
24	Install new control system for wood drying kiln 1–8	20	568	Electricity	288	Yes	Wood
25	Speed control or intermittent operation of circulation fans on wood chamber dryer	3	474	Electricity	319	Yes	Wood
26	Dust filter, frequency converter	3	21	Electricity	480	Yes	Wood
27	Aliant control for wood drying kilns	3	144	Electricity	490	Yes	Wood
28	Install engine heat controllers at planing	3	15	Electricity	524	Yes	Wood
29	Rebuild log sorting	3	35	Electricity	730	Yes	Wood
30	Replace hydraulic drive with frequency control	20	20	Electricity	1259	Yes	Wood
31	Install frequency converters in lathe station	20	10	Electricity	1259	Yes	Wood
32	Interlock transportation over stop signals	1	100	Electricity	0	No	Wood
33	Interlock transportation over stop signals	1	75	Electricity	0	No	Wood
34	Seasonally control freezing and cooling between max and average temperature	1	1	Electricity	0	No	Wood
35	Reduce stand-by losses	2	30	Electricity	81	No	Wood
36	Demand controlled operation of conveyor belts	2	23	Electricity	106	No	Wood
37	Speed control or intermittent operation of circulation fans on wood chamber dryer	1	474	Electricity	319	No	Wood
38	Motor change to higher energy class	5	21	Electricity	1199	No	Wood
39	Optimization of wood drying program	3	125	Fuel	0	Yes	Wood
40	More effective operation of wood drying kilns	3	3580	Fuel	4	Yes	Wood
41	Reduce temperature in garage at wood drying kilns 9–12	1	16	Fuel	16	Yes	Wood
42	Increase efficiency of wood drying	3	1910	Fuel	33	Yes	Wood
43	Isolate incoming culvert to paintery	2	311	Fuel	92	Yes	Wood
44	Isolate branch pipe from culvert to painting ovens	2	38	Fuel	103	Yes	Wood
45	Overhaul wood drying kilns	3	7600	Fuel	133	Yes	Wood
46	Drying kiln - reuse air	3	1200	Fuel	157	Yes	Wood
47	Rebuild chip handling in plant 1 and 2	3	166	Fuel	167	Yes	Wood
48	Encapsulate steaming	3	250	Fuel	201	Yes	Wood
49	Optimization of wood drying program/target moisture content	3	125	Fuel	0	No	Wood
50	Control system for wood drying kilns	3	1850	Fuel	68	No	Wood
51	Heat recovery (heat exchanger in drying kiln)	3	900	Fuel	70	No	Wood
52	Dust separator in stacking	20	41	Fuel	77	No	Wood
53	Increase efficiency of chip ovens	3	860	Fuel	117	No	Wood
54	Pre-heating of drying air	20	1600	Fuel	126	No	Wood
55	Installation of direct driven fan	5	92	Fuel	178	No	Wood

(continued on next page)

Table A1 (continued)

No.	Measure	ID	Energy saved [MW h/year]	Energy carrier	CCE [SEK/ MWh]	Implement-ed [Yes/No]	Industry
56	Replace boiler	3	5500	Fuel	343	No	Wood
57	Replace 2 fans in sawing	3	129	Fuel	347	No	Wood
58	Demand controlled defrosting of refrigerated warehouse	3	40	Electricity	0	Yes	Food
59	Reduced power output in big-bag-drying	3	20	Electricity	19	Yes	Food
60	Clean in place (CIP) diagnosis	20	136	Electricity	46	Yes	Food
61	Improve defrosting	3	10	Electricity	126	Yes	Food
62	Increase capacity of production processes	3	229	Electricity	275	Yes	Food
63	Reparation of heat exchanger in drying kilns, and optimize operation of pumps	3	100	Electricity	340	Yes	Food
64	Install energy efficient electric motors	3	71	Electricity	177	No	Food
65	Increase efficiency in packing	3	241	Electricity	261	No	Food
66	Install free cooling	5	21	Electricity	300	No	Food
67	Pressure pump for dishwater	4	200	Electricity	315	No	Food
68	Fan stops in freezers	3	1	Electricity	1259	No	Food
69	Control operation of drying kilns by moisture content	2	561	Fuel	13	Yes	Food
70	Reduce waste of feedwater	3	36	Fuel	18	Yes	Food
71	Heat recovery from compressor	4	375	Fuel	67	Yes	Food
72	Recover excess heat in production processes	20	100	Fuel	101	Yes	Food
73	Adjustment of burner in boiler	3	415	Fuel	152	Yes	Food
74	Pre-heating of dishwater, 5 centigrades	4	145	Fuel	174	Yes	Food
75	Adjust air flow, install frequency converter to fan if necessary	20	4	Fuel	180	Yes	Food
76	Keep tank warm, move inside/replace	2	175	Fuel	209	Yes	Food
77	New dilute water purification	3	210	Fuel	234	Yes	Food
78	Pre-heating of feedwater, step 2	3	135	Fuel	326	Yes	Food
79	Pre-heating of feedwater, direct heat exchange	3	318	Fuel	396	Yes	Food
80	Cold disinfection for pouring process	3	129	Fuel	24	No	Food
81	Pre-heat cold dilution water with district heating	4	70	Fuel	360	No	Food
82	Pre-heating of grain to factory	3	211	Fuel	537	No	Food
83	Save water from hot water and cooking	3	100	Fuel	630	No	Food
84	Conversion from heating oil to gas	4	428	Fuel	735	No	Food
85	Heating of molasses tank plus roof	2	9	Fuel	1626	No	Food
86	Convert to gas	4	489	Fuel	1802	No	Food
87	Review the controlling of oil separator	3	175	Electricity	0	Yes	Metal
88	Avoid stand-by losses on machines	2	96	Electricity	0	Yes	Metal
89	Stand-by - reduce power output on weekends	2	92	Electricity	0	Yes	Metal
90	Eliminate idling in processing	2	58	Electricity	0	Yes	Metal
91	Central cooling system for wire EDM machines	3	35	Electricity	0	Yes	Metal
92	Reduce stand-by losses	2	34	Electricity	0	Yes	Metal
93	Reduce idling of abrasive blasting	2	25	Electricity	0	Yes	Metal
94	Eliminate stand-by losses of production equipment	2	22	Electricity	0	Yes	Metal
95	Shut down production process during nighttime	2	21	Electricity	0	Yes	Metal
96	Turn off zinc filter during non-production hours	2	20	Electricity	0	Yes	Metal
97	Eliminate idling in processing	2	13	Electricity	0	Yes	Metal
98	Eliminate idling in processing	2	11	Electricity	0	Yes	Metal
99	Reduce idling for sandblasting	2	6	Electricity	0	Yes	Metal
100	Adjust opening of dry and hearth furnace after demand	2	17	Electricity	14	Yes	Metal
101	Information and management of operation personnel	20	33	Electricity	19	Yes	Metal
102	Reduce operating time for drying units	2	48	Electricity	25	Yes	Metal
103	Shutdown machines	2	80	Electricity	30	Yes	Metal
104	Disconnect unnecessary cooling water pumps	3	81	Electricity	39	Yes	Metal
105	Improved cooling of laser	3	15	Electricity	42	Yes	Metal
106	Insulate the oven door to reduce heat loss	3	200	Electricity	63	Yes	Metal
107	Improved insulation of the oven door in foundry	3	100	Electricity	63	Yes	Metal
108	Improve lid on zinc heating tank	3	100	Electricity	63	Yes	Metal
109	Improve sealing of hearth furnace	3	2	Electricity	63	Yes	Metal
110	Insulation of hot pipes	3	15	Electricity	67	Yes	Metal
111	Shut down cooling machine outside of operating times	2	18	Electricity	68	Yes	Metal
112	Shortened operation time and demand operated openings of lacquering	2	15	Electricity	81	Yes	Metal
113	Demand operation of water cooling unit	2	6	Electricity	81	Yes	Metal
114	Turn off the high pressure fan at the production line	2	12	Electricity	102	Yes	Metal
115	Improve insulation of zinc tank during weekends	2	100	Electricity	122	Yes	Metal
116	Reduce stand-by losses	2	30	Electricity	122	Yes	Metal
117	Repair automatic damper fan, welding	3	2	Electricity	126	Yes	Metal
118	Change the dye fixative	3	172	Electricity	220	Yes	Metal
119	Install free cooling in production	3	54	Electricity	233	Yes	Metal
120	Lid on tanks during weekends	2	150	Electricity	244	Yes	Metal
121	Insulate tank, new lid for tank, controlling of heat, etc. at the new line	2	100	Electricity	244	Yes	Metal
122	Rebuild the drying kilns on the hanging line	5	17	Electricity	273	Yes	Metal
123	Lid on tank in the large zinc line	2	47	Electricity	312	Yes	Metal
124	Summer ventilation for laser machine	4	8	Electricity	315	Yes	Metal
125	Cooling system, H + G	20	53	Electricity	333	Yes	Metal
126	Review the routines for surface treatment	2	100	Electricity	488	Yes	Metal
127	Insulate tanks in large zinc line	2	19	Electricity	532	Yes	Metal
128	Cover tanks during nights and weekends	2	78	Electricity	625	Yes	Metal

(continued on next page)

Table A1 (continued)

No.	Measure	ID	Energy saved [MW h/year]	Energy carrier	CCE [SEK/ MWh]	Implement-ed [Yes/No]	Industry
129	Cooling of cutting oil from NC via geothermal heat (exchange during winter)	3	10	Electricity	1889	Yes	Metal
130	Control absorbent filter in production	20	7	Electricity	1937	Yes	Metal
131	Reduce stand-by losses on machines	2	650	Electricity	0	No	Metal
132	Optimization of operating times for heating of baths for concrete, degreasing and anode fans	3	40	Electricity	0	No	Metal
133	Reduce idling of washer/dryer	2	4	Electricity	0	No	Metal
134	Turn off washer/dryer during holidays	2	2	Electricity	0	No	Metal
135	Improve efficiency of cleaning the cutting fluid	3	35	Electricity	18	No	Metal
136	Optimize operation of heating unit	3	60	Electricity	44	No	Metal
137	Reduce overdrying by lowering temperature in drying kiln	2	20	Electricity	61	No	Metal
138	Eliminate idling	2	35	Electricity	70	No	Metal
139	Place a lid over tanks during non-production hours	2	10	Electricity	122	No	Metal
140	Frequency converter for press machines	3	40	Electricity	126	No	Metal
141	Replace controlling system	3	40	Electricity	126	No	Metal
142	Reduce temperature in hot tanks	3	400	Electricity	176	No	Metal
143	Time control on washing	2	5	Electricity	195	No	Metal
144	Reduce idling	2	190	Electricity	257	No	Metal
145	Disconnect cooling machines and use industrial cooling	20	53	Electricity	333	No	Metal
146	Install free cooling to plastic profiles	4	52	Electricity	363	No	Metal
147	Improve efficiency of stirring in water bath	3	13	Electricity	390	No	Metal
148	Improve efficiency of fan system	2	80	Electricity	457	No	Metal
149	Replace the holding furnace	20	1000	Electricity	630	No	Metal
150	Insulation of tank in smaller zinc line	2	8	Electricity	768	No	Metal
151	Lid on tank in the smaller zinc line	2	13	Electricity	780	No	Metal
152	Speed control vacuum cleaner	1	31	Electricity	812	No	Metal
153	Lid on tank, anodeline	2	16	Electricity	1087	No	Metal
154	Reduction of idle power for production processes during weekends	2	80	Electricity	1524	No	Metal
155	Steering of the shaft furnace to keep the shaft loaded	3	1000	Fuel	189	Yes	Metal
156	Improved controlling of shaft furnace	3	500	Fuel	201	Yes	Metal

References

- IPCC. Climate Change 2014: Mitigation of Climate Change. Fifth Assessment Report of the Intergovernmental Panel on Climate Change; 2014.
- European Commission. Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency; 2012.
- European Commission. Proposal for a Directive of the European Parliament and of the Council amending Directive 2012/27/EU; 2016.
- International Energy Agency. Tracking Industrial Energy Efficiency and CO₂ Emissions; 2007.
- Backlund S, Thollander P, Palm J, Ottosson M. Extending the energy efficiency gap. *Energy Policy* 2012;51:392–6.
- Paramonova S, Thollander P, Ottosson M. Quantifying the extended energy efficiency gap-evidence from Swedish electricity-intensive industries. *Renew Sustain Energy Rev* 2015;51:472–83.
- Li L, Wang J, Tan Z, Ge X, Zhang J, Yun X. Policies for eliminating low-efficiency production capacities and improving energy efficiency of energy-intensive industries in China. *Renew Sustain Energy Rev* 2014;39:312–26.
- Stenqvist C, Nilsson LJ. Energy efficiency in energy-intensive industries-an evaluation of the Swedish voluntary agreement PFE. *Energy Effic* 2012;5:225–41.
- Fleiter T, Gruber E, Eichhammer W, Worrell E. The German energy audit program for firms-a cost-effective way to improve energy efficiency? *Energy Effic* 2012;5:447–69.
- Nabitz L, Hirzel S, Rohde C, Wohlfarth K, Behling I, Turner R. How can energy audits and energy management be promoted amongst SMEs? A review of policy instruments in the EU-28 and beyond. *ECEEE Summer Study* 2016:401–15.
- Swedish Energy Agency. Energy in Sweden, fact and figures 2016. Sweden: Eskilstuna; 2016.
- Napp TA, Gambhir A, Hills TP, Florin N, Fennell PS. A review of the technologies, economics and policy instruments for decarbonising energy-intensive manufacturing industries. *Renew Sustain Energy Rev* 2014;30:616–40.
- Thollander P, Cornelis E, Kimura O, Morales I, Zubizarreta Jiménez R, Backlund S, et al. The design and structure of effective energy end-use policies and programs towards industrial SMEs. *Retool a Compet. Sustain. Ind.* ISBN 978-91-980482-4-7, 2014, p. 75–81.
- Thollander P, Paramonova S, Cornelis E, Kimura O, Trianni A, Karlsson M, et al. International study on energy end-use data among industrial SMEs (small and medium-sized enterprises) and energy end-use efficiency improvement opportunities. *J Clean Prod* 2015;104:282–96.
- Backlund S, Thollander P. Impact after three years of the Swedish energy audit program. *Energy* 2015;82:54–60.
- Paramonova S, Thollander P. Ex-post impact and process evaluation of the Swedish energy audit policy programme for small and medium-sized enterprises. *J Clean Prod* 2016;135:932–49.
- Söderström M. Industrial Electricity Use Characterized by Unit Processes - A Tool for Analysis and Forecasting. *Proc. 13th Int. Congr. Electr. Appl.*, June 16–20, Birmingham UK; 1996.
- Meier A, Rosenfeld AH, Wright J. Supply curves of conserved energy for California's residential sector. *Energy* 1982;7:347–58.
- Ma D, Hasanbeigi A, Price L, Chen W. Assessment of energy-saving and emission reduction potentials in China's ammonia industry. *Clean Technol Environ Policy* 2015;17:1633–44.
- Hasanbeigi A, Menke C, Therdyothin A. The use of conservation supply curves in energy policy and economic analysis: the case study of Thai cement industry. *Energy Policy* 2010;38:392–405.
- Tesema G, Worrell E. Energy efficiency improvement potentials for the cement industry in Ethiopia. *Energy* 2015;93:2042–52.
- Morrow WR, Hasanbeigi A, Sathaye J, Xu T. Assessment of energy efficiency improvement and CO₂ emission reduction potentials in India's cement and iron & steel industries. *J Clean Prod* 2014;65:131–41.
- Hasanbeigi A, Morrow W, Masanet E, Sathaye J, Xu T. Energy efficiency improvement and CO₂ emission reduction opportunities in the cement industry in China. *Energy Policy* 2013;57:287–97.
- Worrell E, Martin N, Price L. Potentials for energy efficiency improvement in the US cement industry. *Energy* 2000;25:1189–214.
- Hasanbeigi A, Menke C, Therdyothin A. Technical and cost assessment of energy efficiency improvement and greenhouse gas emission reduction potentials in Thai cement industry. *Energy Effic* 2011;4:93–113.
- Li Y, Zhu L. Cost of energy saving and CO₂ emissions reduction in China's iron and steel sector. *Appl Energy* 2014;130:603–16.
- Sathitbun-anan S, Fungtammasan B, Barz M, Sajjakulnukit B, Pathumsawad S. An analysis of the cost-effectiveness of energy efficiency measures and factors affecting their implementation: a case study of Thai sugar industry. *Energy Effic* 2015;8:141–53.
- Fleiter T, Fehrenbach D, Worrell E, Eichhammer W. Energy efficiency in the German pulp and paper industry - A model-based assessment of saving potentials. *Energy* 2012;40:84–99.
- Sorrell S, Schleich J, Scott S, O'Malley E, Trace F, Boede U, et al. Reducing barriers to energy efficiency in public and private organisations. Brighton; 2000.
- Cagno E, Worrell E, Trianni A, Pugliese G. A novel approach for barriers to industrial energy efficiency. *Renew Sustain Energy Rev* 2013;19:290–308.
- Trianni A, Cagno E. Dealing with barriers to energy efficiency and SMEs: some empirical evidences. *Energy* 2012;37:494–504.
- Rohdin P, Thollander P, Solding P. Barriers to and drivers for energy efficiency in the Swedish foundry industry. *Energy Policy* 2007;35:672–7.
- Fleiter T, Worrell E, Eichhammer W. Barriers to energy efficiency in industrial bottom-up energy demand models - A review. *Renew Sustain Energy Rev* 2011;15:3099–111.
- Fleiter T, Hagemann M, Hirzel S, Eichhammer W, Wietschel M. Costs and potentials

- of energy savings in European industry - a critical assessment of the concept of conservation supply curves. Proceeding ECEEE 2009, 2009, p. 1261–72.
- [35] Lung RB, Mckane A, Leach R, Marsh D. Ancillary Savings and Production Benefits in the Evaluation of Industrial Energy Efficiency Measures. ACEEE Summer Study Energy Effic. Ind., 2005, p. 103–14.
- [36] Worrell E, Laitner JA, Ruth M, Finman H. Productivity benefits of industrial energy efficiency measures. *Energy* 2003;28:1081–98.
- [37] Nehler T, Rasmussen J. How do firms consider non-energy benefits? Empirical findings on energy-efficiency investments in Swedish industry. *J Clean Prod* 2016;113:472–82.
- [38] Svensson A, Paramonova S. An analytical model for identifying and addressing energy efficiency improvement opportunities in industrial production systems – model development and testing experiences from Sweden. *J Clean Prod* 2016.
- [39] Abdelaziz EA, Saidur R, Mekhilef S. A review on energy saving strategies in industrial sector. *Renew Sustain Energy Rev* 2011;15:150–68.